Specification Amendments

Page 10, line 15 through page 11, line 3, please replace with the following amended paragraph:

Referring now to the drawings wherein like reference numerals refer to similar or identical parts throughout the several views, and more specifically to figure 1 thereof, there is shown an electron gun 10. The electron gun 10 comprises an RF cavity 12 having a first side 14 with an emitting surface 16 and a second side 18 with a transmitting and emitting section 20. The gun 10 is also comprised of a mechanism 22 for producing an oscillating force which encompasses the emitting surface 16 and the section 20 so electrons 11 are directed between the emitting surface 16 and the section 20 to contact the emitting surface 16 and generate additional electrons 11 and to contact the section 20 to generate additional electrons 11 or escape the cavity 12 through the section 20 giving the transmitted electrons 21.

Page 11, lines 16-26, please replace with the following amended paragraph:

The present invention pertains to a method for producing electrons 11. The method comprises the steps of moving at least a first electron 11 in a first direction. Next there is the step of striking a first area with the first electron 11. Then there is the step of

producing additional electrons 11 at the first area due to the first electron 11. Next there is the step of moving electrons from the first area to a second area and transmitting electrons 21 through the second area and creating more electrons 11 due to electrons from the first area striking the second area. This process is repeated until the device is shut off by removing the rf power source.

Page 15, line 17 through page 16, line 2, please replace with the following amended paragraph:

where Z and A are the arithmetic mean atomic number and atomic weight, respectively. The secondary emission yield for GaP (plot 1, Fig. 4) at 150 keV from Eq.(4) can be calculated to give δ (150 keV) $\approx$ 28. This can also be seen from Fig. 4 which shows experimentally verified yield curves for GaP and MgO. For MgO (plot 2, Fig. 4) at 20 keV δ (20 keV) $\approx$ 4.9. At δ =28 and T=0.75 for GaP or δ=4.9 and T=0.75 for MgO, there would be gain since Eq.(1) is satisfied.

Page 23, lines 1-8, please replace with the following amended paragraph:

Now, solving self-consistently for the steady state or saturation current density for a beam (charge slab) that is already "bunched", the model for this analysis is shown in Fig.

5. The axial electron bunch length 11 or charge slab thickness is Δ, the axial gap spacing between the parallel plates or electrodes 14 is d, and the beam density is n. The equations of motion for electrons "attached" to the front ("f") (label 3 in Fig. 5) and back ("b") (label 1 in Fig. 5) of the charge slab are evaluated. An electron in the center of the bunch (label 2 in Fig. 5) would have no space charge and travel according to Eq. (5). The equations of motion are

Page 23, lines 10-14, please replace with the following amended paragraph:

$\nu_{f0}(t=t_{f0})$, $\nu_{b0}(t=t_{b0})$, x_{f0}, $x_{f0}(t=t_{f0})$, and $x_{b0}(t=t_{b0})=0$. The subscripts f and b refer to the front and back electrons and the top and bottom sign in Eq. (18), respectively. The quantities E_0 and E_{sc} are the magnitudes of the rf and space charge electric fields, respectively. Define the parameters

Page 26, line 8 through page 27, line 7, please replace with the following amended paragraph:

Equations (25) (plot 1) and (29) (plot 2) are plotted in Fig. 6 as functions of the normalized rf field α_0. The initial position x_{f0}/d is taken to be 0.03 which is consistent with the PIC simulation. The bunch length increases rapidly and then saturates at about 11% of the

cavity spacing. The normalized steady-state current density rises approximately linearly with α_0. This plot of the current density represents the "tuning curve" for this device since α_0 depends on the cavity voltage (V_0), the cavity gap (d), and frequency (ω). A very tolerant tuning curve is a key result. Even if the electric field changed by 30% from, say, beam loading, resonance would still occur but at a lower current density. The range of α_0 plotted represents the approximate range of validity for this simple model. Relativistic effects limit the range of validity for the theoretical model. If the resonant voltage V_0 exceeds 150 kV then relativistic effects start to become more important and the model begins to break down. The model will need to be generalized to include relativistic effects.

Page 28, lines 1-3, please replace with the following amended paragraph:

In Fig. 7, a plot is shown of the resonant electric field (plot 1, d=0.5 cm, plot 2, d=1.0 cm and plot 3, d=1.5 cm) for a number of gap lengths and the Kilpatrick breakdown electric field as a function of rf frequency (plot 4).

Page 29, lines 18-30, please replace with the following amended paragraph:

For these runs, it was assumed that the emission velocity of each secondary electron was a Maxwell in distribution centered around ν_0. Current density and electric field data are saved from probes inserted near the surface of one of the electrodes and also in the center of the electrode. Those electrons which have reached the opposite electrode have usually been emitted within a range of phases $\phi_1 < \phi < \phi_2$. Hence, the electrons participating in the current amplification are actually bunched in the gap region, and in fact the large charge densities of the electron current are limited to a "bunch" emitted between the phases ϕ_1 and ϕ_2. This evidently enables a larger current density to exist in the gap region, as the numerical simulations show. Such a phenomena has been demonstrated theoretically in ~~Section 3.5~~ <u>Fig. 6</u>.

Page 30, lines 7-30, please replace with the following amended paragraph:

Figure 8 shows a series of snapshots in configuration space of the rapid phase bunching of electrons in the cavity. At $t = 0$ electrons are field emitted off the electrode at $x = 0$; they then form a continuous distribution of particles inside the gap before the field emission is turned off at $t = \pi/\omega$. Note that electrons are only emitted from those cells in the center of the cavity in the simulation. At a time $t \approx 0.335\ ns$ <u>(plot 1)</u>, the cavity is filled with a large number of particles and no "bunching" is seen; a short time later, at a time

$t = 0.636\ ns$ (plot 2), the broad distribution of particles have diminished, and a thin bunch of particles can be seen within the cavity. Only those particles which strike the opposite electrode at the right phase and velocity can provide additional electrons (which in turn make their way to the original electrode and continue amplification in the number of particles). At a time of $t = 2.462\ ns$ (plot 3), particles with the "wrong" phase have been filtered out of the simulation, and only particles with the "right" phase are present. The broad distribution of particles have vanished and a narrow bunch of electrons remains and continues to amplify in density. Finally, at a time $t = 3.35\ ns$ (plot 4), the narrow bunch has expanded from space charge and reached a steady state current density. In a laboratory experiment, there will always be a small distribution of electrons with the wrong phase even at late times, since there are many orders of magnitude more particles in a real experiment.

Page 31, lines 1-25, please replace with the following amended paragraph:

Figure 9 shows a plot of the current density J_x across the gap (d=0.5 cm) as a function of time for a simulation with an rf frequency of 1.3 GHz and a voltage amplitude of 4.3 kV. The current density is measured near the second (right-hand) electrode (20, 24 in Fig. 3) which, in an actual experiment, would be the exit screen or grid. Hence, this is the current pulse which will exit the device. The top trace corresponding to positive current density is

that current which is emitted from the second (right-hand) electrode and propagates back to the first electrode. The bottom trace (negative current density) describes the beam that would leave the cavity. Both halves of the curve are not symmetric about $J_x=0$ because the beam pulses have substantially different charge densities and velocities when they cross the position of the probe. In the case for which the current density is positive (i.e., electrons are propagating in the negative x direction), the electrons have just been emitted from the electrode and form a highly dense bunch at a relatively low energy. In the case for which the current density is negative (i.e., electrons are propagating in the positive x direction), the electrons have already crossed the gap and are at a relatively high energy and have spread somewhat due to space charge effects. In this case, the simulation ran out to a total of 9 ns and reached a peak amplitude of 20 A/cm^2 for d=0.5 cm before energy conservation problems begin to become important. At a gap length of 1.0 cm, the resulting current density increased to 50 A/cm^2 with $\alpha_0=0.453$.

Page 32, line 13 through page 33, line 11, please replace with the following amended paragraphs:

It is important to determine the saturated current out of the device as a function of rf frequency. A number of runs at various frequencies were conducted to determine the

current density extracted from the device as a function of frequency. In Figure 12 the results are plotted from a number of simulations for saturated current J_x vs. rf frequency for a cavity with both a 0.5 cm gap <u>(plot 1)</u> length and a 1.0 cm gap <u>(plot 2)</u> length and for $\alpha_0 = 0.453$. Both curves have the same general shape and both obey a power law with $J_x \approx \omega^{3.1}$. The explanation for this scaling law was discussed above. When the gap spacing in the cavity is increased by a factor of two, it is also necessary to either decrease the frequency by a factor of two, or increase the voltage by a factor of four, in order to ensure cavity resonance.

Simulations were also conducted in which the frequency was varied and then measured the micropulse duration in the saturated state (at the seventh cycle). This is shown in Fig. 13. <u>Plot 1 shows the electron micropulse full width at half maximum (FWHM). Plot 2 shows the electron micropulse full width at the base of the pulse.</u> Note that with increasing frequency the micropulse duration decreases. This is because the half-wavelength for allowable emission provides a "bucket" for the pulse width to fill, and as the wavelength decreases there is less for the pulse width to fill, as expected. Note from the figure that $\tau_{FWHM} \propto 1/\omega$; for the value $\alpha_0 = 0.453$ the constant of proportionality is 0.046 is calculated. Hence, the beam pulse width found to be typically only 4.6% of the rf period. The fact that the pulse is such a small part of the rf period is the reason for the name "micro-pulse gun" in contrast to

the usual rf gun [W. Peter, R.J. Faehl, and M.E. Jones, Particle Accelerators **21**, 59 (1987)] where the pulse width is equal to the half-period of the rf wave.

Page 33, lines 12-28, please replace with the following amended paragraph:

It is important to mention that in accordance with the resonant process, the micropulse width decreases as a function of time until saturation (Fig. 14). Plot 1 is the beam full width at different rf cycles. Plot 2 is the beam full width at half maximum at different rf cycles. This is due to the fact that initially particles with all phases are present in the system, and it is only after a few cycle times that the particles with "wrong" phases are flushed out of the system, while at the same time particles with the "right" phase are amplified in number (cf. Fig. 8). These particles with the right "phase" determine the micro-pulse width, the finite width being due to space-charge forces within the pulse which widens the micro-pulse somewhat (see Fig. 8). A distribution of particles within a narrow phase window can still be resonant since particles that were once out of resonance in a single-particle model can be resonant when space-charge is included. This is because a particle with the "wrong" phase can become resonant if the electric fields acting on the particle are such that the particle reaches the opposite electrode at a time a resonant particle would.

Page 34 line 25 through page 35, line 4, please replace with the following amended paragraph:

Figure 16 demonstrates the effect of space charge loading more directly since it plots the current density J_x (plot 1) near the exit grid vs. time with the longitudinal electric field (plot 2) vs. time seen in Fig. 15. The "blips" in electric field correspond to the presence of a particle bunch *emitted off* the exit grid on the way back to the opposite electrode. The micropulse moving toward the exit grid is not seen since it has significantly less charge density (but much larger velocity) than the emitted charge bunch near the exit grid. Figure 16 demonstrates why the space charge limited emission condition cannot be used in our theoretical treatment.

Page 36, lines 4-23, please replace with the following amended paragraph:

In Fig. 17, the "resonant tuning curve" is plotted for the micro-pulse electron gun from the PIC simulations and the theoretical prediction. The importance of this plot is the fact that it describes the "tolerance" of the MPG to deviations in cavity voltage, gap spacing, or frequency, and it indicates the striking agreement between theory and PIC simulation. For simulations with a cavity gap length $d = 0.5$ cm the peak current density is plotted for various frequencies as a function of the normalized rf field α_0. Figure 17 suggests that the MPG has

a high tolerance, and that errors in the field or gap spacing can be easily accommodated in the resonance process. For instance, as is seen from Table 3 at a frequency of 1.3 GHz, the current density J_x at an applied voltage of 2.4 kV is an order of magnitude less than it is at 4.3 kV. However, J_x climbs rapidly from this value as the voltage approaches 6.4 kV, and then turns over and goes to zero again at 9.8 kV. Also displayed in Fig. 17 is the theoretical tuning curve obtained from <u>Eq. (25)</u> ~~the equations in Section 3.5.1~~. As can be seen, the agreement between theory and the two-dimensional PIC simulations is excellent. At high α_0 such that $\alpha_0 > 0.6$ the analytic theory is suspect since it does not include relativistic effects.

Page 41, lines 3-16, please replace with the following amended paragraph:

The accelerating field (after the cavity and second grid) produces a transverse kick as the electrons pass the second grid. However, this field is substantially reduced when we introduce an electrode which makes an angle of 45 ° with the beam exiting the grid. Only the bottom of this 45 ° electrode is shown in Fig. 27. The introduction of this electrode is to focus the micro-pulse (see <u>Figs. 30 and 31</u> ~~Section 3.10~~); the angle of $45°$ is optional for high energy electrons [W. Peter, Journal of Applied Physics **71**, 3197 (1992)]. For emission, this angle becomes $3\pi/8$, that is, the Pierce angle. The fact that this $45°$ electrode will

reduce the transverse fields by an order of magnitude is a fortunate outcome of our studies. This also allows for higher gradients outside the cavity. Thus, the kick from the second grid does not significantly affect the emittance.

Page 42, lines 1-12, please replace with the following amended paragraph:

Figure 28 shows the emittance and transmission results using an ac voltage. The normalized emittance starts at zero and grows to 2.5 mm-mrad just before the first grid. The emittance after both grids decreases as the number of grid wires per 5 mm radial extent increases. With reasonable transmission (52%), an emittance within a factor of two of its value before the grid can be obtained. If "rms addition" is applied to the secondary source emittance of 7 mm-mrad ~~(Sect. 3.4.1)~~ and to those on Fig. 28 a range of 9-18 mm-mrad as the final extracted beam emittance is obtained. For the given space charge, the best emittance to charge ratio of 3 mm-mrad/nC is obtained, including all sources of emittance for the extracted beam.

Page 56, lines 8-27, please replace with the following amended paragraph:

For a typical injector application, a finite magnetic field at the emitting surface in the MPG is not used because it would impair the emittance downstream. For this reason,

an alternative to magnetic focusing within the MPG is proposed, namely to shape the cavity of the MPG so it employs moderate electrostatic focusing. ~~As in Section 3.10, classical~~ Classical Pierce shaping cannot be directly used in the present situation since the micropulse from the emitter (Fig. 46) is not space-charge limited. In this case, the appropriate electrode shaping can be solved for from the theory presented for Figs. 30 and 31~~in Section 3.10~~. Note that this focusing is essentially "one-way", i.e., the micropulse emitted off the exit grid 20, 24 which returns to the emitting surface S 16 will be slightly *de-focused* during its transit. However, a slightly de-focused returning pulse can be tolerated since its only *raison d'etre* is to provide a source of electrons for creation of anew batch of secondary electrons off the surface S 16. Hence, the only possible disadvantage of a de-focused returning micropulse would be to cause some secondary electrons to strike the opposite wall of the cavity outside of S 16 and thus to represent a possible decrease in the cavity *Q*.